

Liquid Metal Pump Technologies for Nuclear Surface Power

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Abstract – Multiple liquid metal pump options are reviewed for the purpose of determining the technologies that are best suited for inclusion in a nuclear reactor thermal simulator intended to test prototypical space nuclear surface power system components. Conduction, induction, and thermoelectric electromagnetic pumps are evaluated based on their performance characteristics and the technical issues associated with incorporation into a reactor system. A thermoelectric electromagnetic pump is selected as the best option for use in NASA-MSFC's Fission Surface Power-Primary Test Circuit reactor simulator based on its relative simplicity, low power supply mass penalty, flight heritage, and the promise of increased pump efficiency over those earlier pump designs through the use of skutterudite thermoelectric elements.

I. INTRODUCTION

It is the purpose of this paper to present a survey of various available liquid metal pumping technologies that could be incorporated into a flight demonstration fission surface power reactor. This survey includes a listing of the various strengths and weaknesses of each option, and focuses special attention on identifying the primary developmental issues that would need to be addressed and resolved before deployment in a space-qualified system. The present survey is similar but more comprehensive than that performed by Determan and Baker¹, and is aimed at providing recommendations of pump technologies that are best suited for the Fission Surface Power-Primary Test Circuit (FSP-PTC) hardware demonstration effort at NASA-MSFC. These recommendations are based on comparisons between the capability, reliability, availability, mass, and complexity associated with development and implementation of each pump option.

For this paper, the assumptions are as follows:

- Working Fluid: NaK78
- Fluid Temperature: 840-800 K
- Δp : 7.5-10 kPa
- Volume Flow Rate: 13.2-15 GPM
- Operational time: 1 year nominal

All the pump options discussed in this paper are electromagnetic in nature, meaning that body forces are directly applied to the liquid metal by interacting currents and magnetic fields. Mechanical pumps have been omitted from the review as it is desirable to avoid wear issues,

mechanically induced vibrations, and sealing difficulties associated with incorporating reciprocating or rotating machinery into a liquid metal flow system².

II. REVIEW OF ELECTROMAGNETIC PUMP TECHNOLOGIES

Electromagnetic (EM) pumps³ exploit the fact that liquid metals are conducting fluids capable of carrying current. By orienting a magnetic field perpendicular to a current passing through the liquid metal, a streamwise $\mathbf{j} \times \mathbf{B}$ Lorentz body force is exerted on the fluid. This has the effect of either accelerating the conducting liquid as it passes through the electromagnetic pump or increasing the pressure head within the liquid. A relatively universal limit on all EM pumps is that at flow velocities exceeding ~ 9.14 m/s cavitation occurs, introducing instabilities and oscillations that can reduce pump performance³.

II.A. Conduction Pumps

In conduction pumps, current is directly conducted into the fluid through electrodes that are typically attached to the outer wall of the duct containing the liquid metal. There are two basic variants of this pump – direct current (DC) and alternating current (AC). In both variants, the fluid is driven by the exact same physical processes. Consequently, these pump types share many common loss mechanisms.

DC Conduction Pumps

The DC conduction pump³⁻⁷ is the simplest EM pump design (see Fig. 1), employing either permanent magnets or electromagnets to generate the field within the liquid metal. It represents a simple design, possessing no moving parts, and can easily be integrated into a flow loop. An idealized schematic of a DC conduction pump is presented in Fig. 2, where the magnetic field B and the current I are both perpendicular to the flow vector.

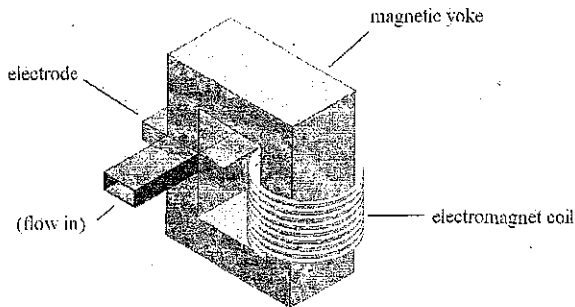


FIG. 1: Schematic representation of a DC conduction pump.

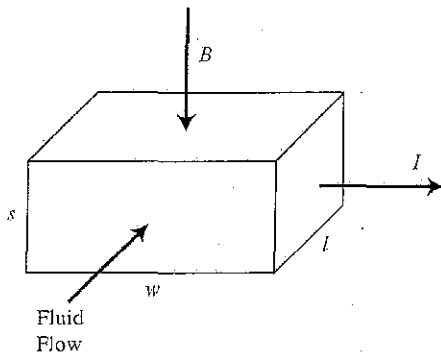


FIG. 2: Idealized schematic of a DC electromagnetic pump.

While their design is simple, DC conduction pumps have several loss mechanisms that, depending upon the operating regime of the pump, can seriously degrade performance. These loss mechanisms include: magnetic braking (back-EMF), wall currents, end currents, armature effects, and Ohmic heating. The scaling results presented in Table I demonstrate that different loss mechanisms dominate depending upon the operating conditions of the pump. For example, if the flow rate is high, the back-EMF losses will be great. If the current is high, Ohmic heating and armature effects become increasingly large energy sinks. Since it contains multiple terms, wall current losses can potentially be mitigated by careful design.

The loss scaling indicates that for a DC conduction pump operating in the high current or high flow rate regime, the power and performance losses can become prohibitively large, making this design unattractive.

Ohmic heating in the cabling connecting the power conditioning unit to the pump can pose an additional challenge at high current levels and require a significant amount of cabling, which can, in turn, burden the overall design with a significant mass penalty. This problem can be partially addressed by locating the power conditioning equipment as close to the pump as possible, but the closer it gets to the reactor, the more radiation tolerant it must be. Finally, when considering DC conduction pumps, the power conditioning needs of the system must be addressed. The pump requires high currents delivered at low voltages (~ 1 V). Designing a power processing unit capable of satisfying this requirement is not trivial and should not be neglected when considering this type of pump.

TABLE I: Loss mechanism scaling in conduction pumps.

Loss Mechanism	Effect of Loss	Loss Scaling
Back-EMF	Power Loss	$\sim B^2 \dot{V}^2 / \rho$
Wall Currents	Power Loss	$\sim (IR - Bu)^2 / R_w$
Armature Effects	Nonuniform Press.	$\sim I$
Ohmic Heating	Power Loss	$\sim I^2 R$

AC Conduction Pumps

In an AC conduction pump^{3,5,6} (see Fig. 3), the current conducted into the fluid and the applied magnetic field are both time-varying. While this pump is more complicated than the DC variant, the physics of the pumping mechanism are exactly like those in a DC conduction pump. The use of AC power allows for the use of transformers, making it easier to generate the high-current, low-voltage power required by a conduction pump using a higher-voltage/lower-current power processing unit input.

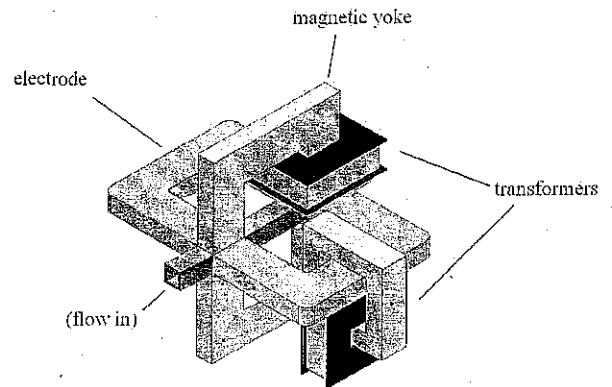


FIG. 3: Schematic representation of an AC conduction pump.

While the time-varying nature of the AC pump reduces the resistive power loss in the external cabling, the loss mechanisms cited in Table I are still present. In addition, AC pumps suffer from eddy-current losses and losses associated with the phase difference between the magnetic field and the applied current. Like its DC counterpart, this type of pump becomes overly inefficient at higher flow rates and current levels.

II.B. Induction Pumps

Induction pumps^{3,5-7} (as shown in Fig. 4) differ from conduction pumps in that current in the conducting fluid is induced by a traveling magnetic field. Variants include the flat linear induction pump (FLIP), annular linear induction pump (ALIP) and spiral induction pump (SIP). A time-varying current passed through sets of wires external to the fluid produces a magnetic field which travels through the conducting fluid as a wave with a given phase velocity. The magnetic field induces currents in the fluid which interact with the traveling magnetic field to yield a net Lorentz force on the liquid metal. The optimization of pump efficiency is a complex problem without closed-form solution.

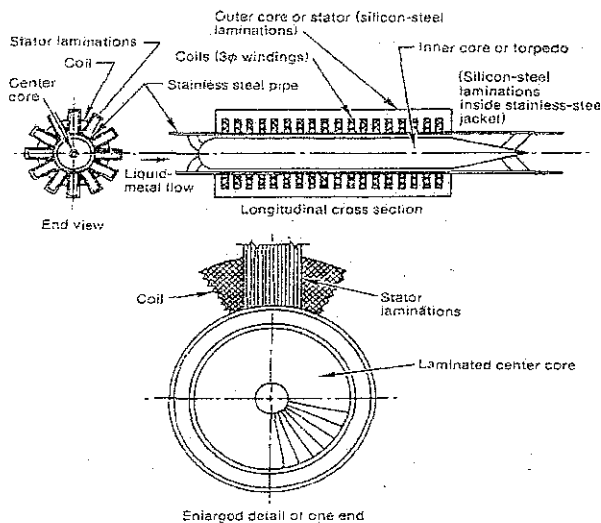


FIG. 4: Internal view of an Annular Linear Induction Pump (ALIP)³.

The primary advantage of induction pumps is that they are relatively efficient when applied to systems requiring relatively high flow rates. Induction pumps can also tolerate liquid metals at higher temperatures since the magnetic field is induced and the external windings are not in direct contact with the fluid.

Induction pumps are not well suited for systems that operate at either low power or low volumetric flow rates. While it is relatively easy to develop a power conditioning system capable of yielding the correct current, voltage, and

frequency characteristics for efficient pumping, several of these units are typically required to produce the traveling magnetic wave. For high power systems, the mass fraction associated with the power conditioning system can be relatively small. However, in low power systems, because there is such a high initial mass penalty associated with multiple power units, the mass penalty can become prohibitively large.

II.C. Thermoelectric Pumps

Thermoelectric pumps represent an interesting alternative to the DC conduction pumps previously discussed. We proceed by first describing how these pumps operate and then highlight some recent technological developments that may prove enabling for this pump option.

Thermoelectric Pumps

Thermoelectric (TE) pumps⁸ (see Fig. 5) are similar to DC conduction pumps in many respects. A magnetic field is typically applied using permanent magnets and fluid is pumped by a Lorentz body force arising through the interaction of a current applied perpendicular to both the magnetic field and the flow vector.

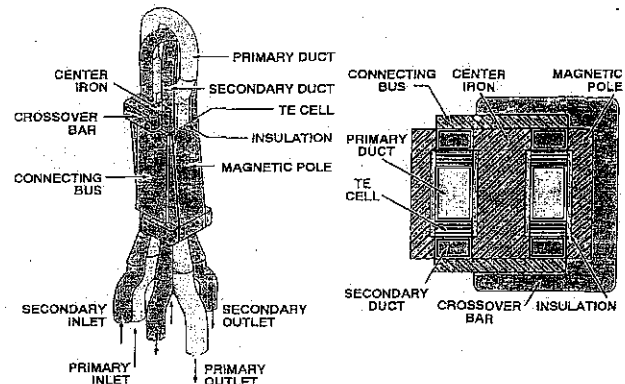


FIG. 5: TE pump design from the SP-100 reactor⁹.

A TE pump is fundamentally different from a standard conduction pump in that the current flowing through the liquid metal is derived directly from the thermal power contained in the hot liquid-metal flow. The method of extraction of this power is a thermoelectric mechanism called the Seebeck effect. Briefly stated, if two dissimilar materials (typically semiconductors) are connected and the junctions held at two different temperatures, a voltage difference ΔV will develop between the junctions proportional to the temperature difference ΔT , and current will flow. A measure of the thermoelectric effectiveness of different material combinations is the Seebeck coefficient α , which is defined as $-\Delta V/\Delta T$.

The loss mechanisms in a TE pump are the same as those cited in Table I. However, the current levels and flow rates are limited to much lower values when compared to a standard DC conduction pump because the thermoelectric mechanism generating current in the channel cannot simply be fixed at an arbitrary value independent of the liquid metal temperature. As a consequence, the current levels and flow rates remain low and no single loss mechanism is expected to dominate the performance in this type of pump.

TE pumps have several advantages. They are relatively simple to understand and can be modeled using knowledge of DC conduction pumps. Since TE pumps derive their power directly from the heated liquid metal and require no external input, they can avoid many of the difficulties associated with startup (self-starting). TE pumps are also 'self-regulating' devices. For example, if the liquid metal exiting a reactor increases in temperature, the pumping rate of a TE pump will also increase, pushing liquid metal through the reactor faster and reducing the temperature of the coolant. The pump power conditioning units and interconnecting cables found in other EM pump schemes can be eliminated in the TE pump design where electrical current is produced within the pump itself. Finally, thermoelectric pumps have a flight heritage, having successfully operated in the SNAP 10A reactor⁸. In addition, there has been considerable additional work performed more recently in the SP-100 reactor program^{9,10}.

Care must be taken when integrating the pump into the flow loop. Thermoelectric conversion of heat to electricity is generally an inefficient process (1-5%). At high temperatures delamination or degradation of the semiconductor junctions must be considered. The TE elements must remain conductively coupled to the rest of the current conduction circuit for the pump to operate. TE pumps are not well suited for operation at high flow rates. A TE pump unit typically employs radiators to yield a proper temperature difference between the junctions. However, it is unclear if this will actually add an undue mass burden to the system since other pump variants also require radiators for cooling purposes. A full systems-level analysis would be required to show whether a TE pump had a specific power (W/kg) advantage over other pumps that required external input from power conversion and conditioning units and interconnecting cabling to interface with the pump.

Skutterudite Thermoelectric Pumps

Recently, new thermoelectric materials and technologies have emerged as potential candidates for incorporation in TE pump designs. Skutterudites¹¹ are a class of open-lattice structure materials that are interesting because they could replace the lead-telluride (PbTe) and

silicon-germanium (SiGe) semiconductors used in previous state-of-the-art TE pumps.

Skutterudites possess a higher Seebeck coefficient. In addition, thermal to electric conversion efficiencies in excess of 10% have been achieved^{12,13}. As a consequence, a greater voltage and greater current can be imposed on the pump allowing for an increase in the pressure rise and flow rate within the pump relative to one using non-skutterudite thermoelectric elements. However, the long-term degradation and delamination characteristics of skutterudites are not well known at present.

III. COMPARISON OF PUMPING TECHNOLOGIES

Presented in Table II is a lengthy, though not exhaustive, listing of the performance characteristics of several different liquid metal pumps. The table contains either the predicted or measured pump performance for a wide range of flow parameters in many different conduction, induction and TEM pumps. Pump efficiency η is defined as the ratio of pumping power to input electrical power (not including the efficiency of conversion from thermal to electrical power), and is given as

$$\eta = \frac{\Delta p \dot{V}}{P_{IN}} \quad (1)$$

where Δp is the pressure rise across the pump and \dot{V} is the volumetric flow rate.

Several points are clearly illustrated in the table:

1. The AC conduction pump is notably inefficient since the input electrical power is used to produce both the input current and applied magnetic field.
2. Excluding the AC conduction pump, there is significant overlap in the operating envelopes of all the pumps, implying that if the electrical power is available any electromagnetic pump can provide a requisite flow velocity and pressure change.
3. As a consequence, the final decision should be based on the systems-level impact the pump will have on the reactor unit (pump specific power and development cost).

A comparison of general strengths and weaknesses inherent to each electromagnetic pump technology is presented in Table III. The listings in this table and Table II are used in the following section to justify the pump recommendations and help identify developmental issues associated with the choices.

TABLE II: Performance of various electromagnetic pump designs. (* - Does not include the efficiency of conversion from thermal to electrical power. ** - Power factor assumed between 0.5 and 1 for calculation of the input power and pump efficiency. † - Predicted performance values.)

Pump Type	Input Power [kW _e]	Δp [kPa]	Flow Rate [gal/min]	Pump Efficiency* [%]	Liquid Metal (Operating Temp)
<i>Conduction Pumps</i>					
DC ^{†,5}	2.6	414	10	12	Bi (200 °C)
DC ⁴	14.2	276	300	44	NaK (250 °C)
DC ^{†,5}	261	517	2000	30	Bi (550 °C)
DC ⁵	649	517	8300	~50	Na (410 °C)
DC ¹⁴	1.9	187	50	36	Hg
DC ^{†,15}	~20	138	420	19	Li (1150 °C)
AC ⁵	1.25	103	6	4	Hg
AC ¹⁶	-	69	20	-	NaK (400 °C)
AC ¹⁷	1.8-3.6**	90	20	3-6**	NaK
<i>Induction Pumps</i>					
ALIP ⁵	8.6	97	420	36	NaK (175 °C)
ALIP ^{†,5}	29	345	400	36	Na (500 °C)
ALIP ⁵	721	517	8300	45	Na (400 °C)
ALIP ^{†,15}	30	138	420	15	Li (1150 °C)
FLIP ¹⁴	70	276	1200	36	Na (370 °C)
FLIP ^{†,15}	28	138	420	16	Li (1150 °C)
SIP ^{†,5}	3.6	414	25	22	Na (400 °C)
SIP ¹⁴	35	276	312	18	Na (400 °C)
SIP ^{†,15}	28	138	420	16	Li (1150 °C)
<i>Thermoelectric Pumps</i>					
TE ⁸	15.9 W _e	7.6	13.2	39.7	NaK (540 °C)

TABLE III: Listing of the primary advantages and disadvantages of different electromagnetic pumps.

Pump Type	Advantages	Drawbacks
DC-Cond.	<ul style="list-style-type: none"> Simple design Low pump mass 	<ul style="list-style-type: none"> High current cabling mass High <i>I</i>, low <i>V</i> power conditioning Armature and Ohmic heating losses
AC-Cond.	<ul style="list-style-type: none"> Power conditioning using transformers 	<ul style="list-style-type: none"> Low pump efficiency High transformer cooling requirements Pulsating body force Armature and eddy-current losses Large pump, difficult to integrate
Induction	<ul style="list-style-type: none"> Power conditioning relatively lightweight at higher power Efficient over broad pump size and input power 	<ul style="list-style-type: none"> Complex design Pulsating body force End and eddy-current losses Multiple power conditioning units for production of traveling wave If stators delaminate, winding cooling is reduced
TE Pump	<ul style="list-style-type: none"> Low system mass Simple design No external electrical input required Self-starting and self-regulating 	<ul style="list-style-type: none"> Conductively coupled TE-elements Failure if TE-elements delaminate or lose conductive coupling Armature and Ohmic heating losses

IV. RECOMMENDATIONS, DEVELOPMENT ISSUES, AND RISK MITIGATION

Several different liquid metal electromagnetic pumps have been reviewed for the purpose of selecting pump options for the FSP-PCT non-nuclear thermal simulation system. As a consequence of its low system mass, relative design simplicity, desirable performance characteristics, and flight heritage, the TE pump is recommended for incorporation into the design. It is further recommended that skutterudite thermoelectric (TE) elements be employed in this system to maximize its efficiency and demonstrate what appears to be a very promising advancement.

A DC conduction pump is recommended as a fall-back option partially because the design is simple and the required pump power input is expected to be low. Consequently, the cabling connecting the power processing system to the pump should not become overly heavy and no single loss mechanism should dominate the pump's performance. In addition, if an unforeseen or time-consuming issue arises during the implementation of a TE pump, that design can be converted with the least amount of effort into a DC pump accepting input from an external power supply. This would allow for validation of the design's pumping capability while leaving open the possibility for later integration of the TE pump should the technical issues be resolved in parallel with the FSP-PCT development effort.

Induction pumps are ruled out for this development effort. The flow rates and required pressures simply do not merit the additional complexity of several power conditioning subsystems capable producing the multi-phase electric power necessary to generate traveling magnetic waves in the system. In addition, the stator/winding design process and the heat transfer issues associated with stator delamination further complicate this pump option, making its development and implementation time-consuming and relatively expensive.

The primary issues associated with the design and implementation of a TE pump stem from the inclusion of TE elements in the system. Two principle developmental problems, which are interrelated, may arise. Conductive-coupling of the TE elements to the rest of the current conduction circuit must be maintained for pump operation. Also, the lifetime of the TE elements and junctions at elevated temperature are in question and evaluation of performance as the junctions degrade is required.

V. CONCLUSIONS

A review of several electromagnetic pump technologies leads to the conclusion that a thermoelectric electromagnetic pump is the best option for inclusion on

the FSP-PCT system at NASA-MSFC. It offers a desirable combination of simplicity and low system mass and should be easily capable of operating within the required performance envelope. This pump option has also proven itself reliable in the past, accumulating 43 days of in-space operation in the SNAP 10A flight system and accruing 10,000 hours in ground testing of the SNAP 10A flight spare system. Recent advances in thermoelectric elements promise an increase in pump efficiency over previous TE systems. The primary developmental issues that must be addressed are the lifetime of the thermoelectric elements and the bonds that conductively couple the different elements in the circuit. These issues are best addressed in small-scale tests performed before a full-size pump is fabricated.

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NOMENCLATURE

B	= magnetic induction [T]
I	= current [A]
P_{IN}	= input power [W]
R, R_w	= resistance [Ω]
u	= flow velocity [m/s]
V	= voltage [V]
\dot{V}	= volume flow rate [Gal/min]
α	= Seebeck coefficient [V/ $^{\circ}$ K]
Δp	= pressure rise [Pa]
ΔT	= temperature change [$^{\circ}$ K]
ΔV	= voltage change [V]
η	= pump efficiency
ρ	= density [kg/m ³]

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